A Thesis

entitled

Knee and Ankle Biomechanics during Squatting with Heels On and Off of the
Ground, With and Without Body Weight Shifting

by

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Submitted to the Graduate Faculty as partial fulfillment of the requirements for the
Masters of Science Degree in Bioengineering

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Abstract of

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Squatting is a common daily activity in many cultures. In western cultures squatting is used in sports, work, and leisure, and in Asian cultures squatting is also used for daily activities such as using the restroom and waiting. During periods of long squatting activities it is common for people to shift their weight to maintain comfort. Additionally, various postures are often employed when squatting; the two most common being the Asian Squat, which involves the heels remaining on the ground throughout the squat, and the Catcher’s Squat in which the heels are raised from the ground throughout the movement. However, neither the biomechanics of body weight shifting nor the specific effects of posture on squatting has been well studied. Furthermore, the muscle activity used to maintain these postures is not well known. The purpose of this study was to examine the biomechanics of the knee and ankle joints with and without body weight
shifting during a deep squatting activity while the heels were both on and off the ground. This study also looked at the muscle activities associated with each squatting activity.

The testing protocol was approved by the IRB of the University of Toledo. Four males and four female volunteers were each instrumented with twenty-one reflective markers and ten EMG sensors. Four separate squattting tasks were performed with a motion analysis system. The first task was a stand then squat test keeping the heels on the ground. The second task was a stand then squat test while lifting the heels off of the ground. The third task was an Asian squat with weight shifting. The final task was a Catcher’s squat with weight shifting. Each task was repeated until 5 successful trials were recorded. The data were collected and processed using Cortex software. The KinTools RT kit, EMGworks Analysis, and Excel were used to calculate and analyze the data. The trials from each individual volunteer were averaged over time for each task. The data from the four tasks were then averaged together to get average male and female volunteer data sets. Finally the trials from all volunteers were averaged together to get one average data set for each squatting activity.

On average lifting the heels off the ground caused the knee extension moments and the ankle plantarflexion angle to increase compared to keeping the heels on the ground. Shifting weight caused the knee extension moments to increase during both the Asian and Catcher’s squats, but did not significantly change the knee flexion angles. Shifting weight also caused the ankle planterflexion moment and ankle dorsiflexion angle to increase. The Catcher's squat caused the greatest increase in the knee extension moment when weight shifting occurred.
The quadriceps and tibialis anterior muscles experienced more activity during the Asian squat, while both heads of the gastrocnemius experienced more activity during the Catcher’s squat. Weight shifting did not significantly change the muscle activities, though they tended to increase during weight shifting. Additionally, it was found that while the male volunteers tended to have greater knee extension moments, knee flexion angles, and ankle plantarflexion moments than the female volunteers, there was no significant difference between any of the joint moments, angles, or muscle activities.

Because of these findings it is recommended to keep the heels on the ground when squatting for long periods of time, and to avoid weight shifting by standing up to maintain comfort in order to reduce joint moments and potential increases to wear. However, this may require more endurance to be built up in the muscles. The significance of this work cannot be overlooked, since squatting is a daily activity performed by people throughout the world, and may have implications for the development and response of a variety of orthopedic conditions.
I would like to dedicate this body of research to my wonderful wife, Brianna, whose continued love and support causes me to strive to be better than I am.
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Chapter 1

Introduction

The knee is a very important joint that allows us to go about our daily lives. It is a highly developed structure with many parts that work together to allow the knee to function properly. The bones comprising the knee joint – the femur, tibia, and fibula – allow the knee joint to support large loads. The quadriceps and hamstring muscle groups provide the force needed to maintain balance and move the joint voluntarily, and the menisci help to provide stability and support within the knee joint as it moves. The cartilage in the knee joint helps to lubricate the surfaces of the bones. There are many different problems that can affect the function of the knee joint, such as muscle weakness, muscle degeneration, ligament injury, and osteoarthritis. The deterioration of the cartilage in the knee is a common joint problem in today’s society. There are several factors that can cause this degeneration such as diet, age, genetics, injury, and lifestyle. The mechanical loading of the knee during sports and other rigorous activities performed throughout the day can cause the degeneration of cartilage in the knee to occur over time
as well.[1] Once the cartilage has been degraded it becomes hard for patients, surgeons, and physical therapists to aid in the recovery due to its complex structure.[2] The purpose of this study is to look at deep squatting, a common daily activity in many cultures, and how it affects the biomechanics of the knee and ankle joints as well as their primary muscles in various squatting positions both with and without weight shifting.

1.1 Deep Squatting

Squatting is a common activity found in many cultures. Asian cultures use squatting for various daily activities such as working close to the ground, reading, using the restroom, or just waiting in a location.[3] In western cultures squatting is used in sports, such as the catcher in baseball, as well as in some jobs, such as mason workers. A deep squat is when the angle of the knee joint is greater than 100°. Many studies have been done in the past to look at the biomechanics and muscle activities during squatting activities where the knee angle was between 0° and 100°.[4] Kim et al did a study to determine the relationship between the range of motion of the hip, knee, and ankle joints and the ability to perform squats of different depths with the heels off the ground using kinematics.[5] Some previous studies have also looked at different aspects of deep squatting activities. Butler et al did a study to see if different biomechanical strategies were used by volunteers who scored differently on the Functional Movement Screen deep squat test.[6] Fukagawa et al did a study to observe the changes in the kinematics of the hip, knee, and ankle joints during a deep squat as a result of age.[7] Toutoungi et al did a study to determine the forces on the cruciate ligaments during a squat using motion capture, a single force platform, and EMG with heels both on and off the ground.[8]
Desloovere et al did a study to look at the reliability of motion capture measurements on various movements, including both mild and deep squatting, using motion capture and two force platforms while allowing the heels to be lifted from the ground if needed.[9]

1.2 Anatomy of the Knee and Function

The knee is one of the most complex joints in the human body. This complexity is there to support the variety of functions the knee joint must accommodate, including the ability to support body positioning, provide motion, transmit forces, and absorb forces. Support of the position of the body is given by the two weight bearing bones in the leg, along with the major muscles. The femur is the main weight bearing bone in the thigh, while the tibia (medial bone) provides the weight bearing structure of the shin. The patella is another bone that sits over the knee joint anterior to the femur, but helps to transmit force from the quadriceps muscles to the tibia, rather than providing support.

The quadriceps muscle group is comprised of four muscles – the vastus medialis, the vastus lateralis, the vastus intermedius, and the rectus femoris – and is one of the two main muscle groups in the knee joint. The vastus medialis runs along the medial side of the thigh with its origin at the intertrochanteric line. This muscle acts to extend the knee and adduct the thigh. The vastus lateralis runs along the lateral side of the thigh with its origin located at the greater trochanter. This muscle acts to extend the knee, and sometimes can abnormally displace the patella. The vastus intermedius runs along the center of the thigh with its origin located at the anterior side of the lateral aspect of the proximal end of the femoral shaft. This muscle acts only to extend the knee. The rectus femoris runs over-top of the vastus intermedius with its origin located on the anterior
interior iliac spine. The rectus femoris acts to extend the knee as well as flex the hip. All four muscles come together at the quadriceps tendon at the distal end of the femur. The quadriceps tendon then connects to the patella. A depiction of the quadriceps muscle group can be seen below in Figure 1-1.

![Image of quadriceps muscles](Picture Courtesy of fitstep.com)

**Figure 1-1 – Anterior view of the right leg, showing the quadriceps muscles (Picture courtesy of fitstep.com)**

The other muscle group is the hamstrings muscle group, which includes the semitendinosus, semimembranosus, and biceps femoris. The semitendinosus runs along the medial side of the posterior of the thigh, with its origin located at the ischial tuberosity. The semitendinosus is inserted at the medial aspect of the proximal end of the tibial shaft, and acts to extend the hip as well as flex the knee. The semimembranosus is located directly next to the semitendinosus and runs along the medial edge of the posterior of the thigh, with its insertion also at the ischial tuberosity. The semimembranosus is inserted at the medial condyle of the tibia, and acts to extend the hip
as well as flex the knee. The biceps femoris runs along the lateral side of the posterior of the thigh. The biceps femoris has two heads, a long and a short head, with their origins at the ischial tuberosity and the distal end of the femur respectively. The biceps femoris also has two insertion points at the head of the fibula and the lateral condyle of the tibia, and acts to flex the knee and extend the hip. A depiction of the hamstrings muscle group can be seen below in Figure 1-2.

![Figure 1-2](image_url)  
*Figure 1-2 – Posterior view of the right leg, showing the hamstrings muscles (Picture courtesy of fitstep.com)*

There are four major ligaments in the knee joint that help to stabilize the knee. They are the Anterior Cruciate Ligament (ACL), Posterior Cruciate Ligament (PCL), Medial Cruciate Ligament (MCL), and the Lateral Cruciate Ligament (LCL).

Another important part of the anatomy of the knee joint is the meniscus. There are two menisci that sit between the tibia and the femur. These menisci are crescent shaped
wedges that perform two main functions. The first is to help transfer the loads between the femur and tibia as well as stabilize the knee joint during motion. Because the tibia and femur have different shapes they come in contact with each other in only two points during motion. The menisci are fibrocartilaginous structures which fit between the femur and tibia to help spread the joint forces over a larger contact area. The menisci are attached to the top of the tibia along their outer edge, and move slightly during motion to keep the contact between the femur and tibia at a maximum.

A layer of articulating cartilage is also present on the surface of the femoral condyles, the tibial plateau, and the back of the patella. These articulating cartilages give the knee joint a smooth surface and lubrication during motion to help reduce the friction of the joint.

Because the knee is such a complex joint with many different bones and tissues, there are a lot of things that can affect the function of the knee. Injuries to the ligaments in the knee can cause the joint to become unstable during movement. Injuries to the ACL are common in sports, especially in women, and PCL injuries happen on occasion as well. Muscle weakness or injury can also inhibit the knee’s ability to move and support weight. Injuries to the bone can make weight bearing painful, and osteoporosis can cause the bone to break more easily around the knee joint, making movement very uncomfortable for someone. Osteoarthritis or damage to the cartilage can also cause the surface of knee joint to become rougher giving it a higher friction and making it harder to move. Degradation can also cause the knee joint to become inflamed and stiff, further adding to the difficulty in moving the joint. This study was done with the intention of
looking at the biomechanics and muscle activity of the knee and ankle during a deep squat both with and without weight shifting.

1.3 Anatomy of the Ankle and Function

The ankle is another of the large joints in the body. The ankle joint is comprised of three main bones. The tibia provides the main articulating surface of the shin in the ankle joint. The fibula helps to provide constraint in the shin to keep the ankle joint from translating medially. The talus provides the articulating surface in the foot. The ankle joint primarily undergoes flexion and extension movement, but does allow for rotation and some inversion or eversion.

There are three main muscles that work in the ankle joint. The tibialis anterior runs along the anterolateral tibial shaft with its origin at the lateral tibial condyle. The tibialis anterior is inserted at the base of the 1st metatarsal and acts to dorsiflex the foot as well and helping to invert and adduct the foot. The gastrocnemius muscle runs along the posterior side of the shin and is what is commonly referred to as the major calf muscle. The gastrocnemius has two heads with inner head originating at the medial femoral condyle and the outer head originating at the lateral femoral condyle. This muscle acts to plantarflex the foot and help flex the knee, as well as helping to stabilize both the ankle and knee. The third muscle is the soleus muscle, which runs along the posterior part of the shin and deep to the gastrocnemius. The soleus acts primarily to plantarflex the foot. Both heads of the gastrocnemius and the soleus muscle come together at the Achilles tendon and are then inserted in the calcaneus. A depiction of the location of all three muscles can be seen in Figure 1-3.
1.4 Electromyography and Muscle Force

Electromyography is the technique used to record changes in electrical activity within muscles. This is done using special electrode sensors that are placed on the muscles to pick up the electrical potentials. There are three main types of EMG sensors that can be used. Surface electrodes are sensors that are placed on top of the skin near the belly of the muscle in order to detect electrical changes through the skin. These types of sensors are commonly used for their ease of application and lack of penetration into the
volunteer’s skin, but they are only able to be used for large muscles that are close to the surface of the skin. Another type of electrode is the percutaneous inserted sensor that is inserted through the skin and directly into the muscle. These are often needle electrodes and offer a high degree of specificity in muscle selection, and can be used on deeper muscles. The third type of electrode is a surgically implanted sensor. These sensor types are not often used due to the requirement of surgery in order to implement them.

Once the sensor is on the muscle it picks up the currents from the motor neurons used as activation signals to contract the muscle, and the sensor is able to read the amount of voltage potential across that muscle. As the muscle contracts it produces a tension force on the bones between the muscle’s origin and insertion points. This causes a moment about the joint which, if large enough to overcome the segment weight and any external forces, will cause the segment to move. There are three ways that researchers have tried to determine the amount of force output by a given muscle based on the EMG sensor readings. The first is to use mathematical modeling and optimization in order to estimate the individual muscle forces. The second is to find a direct relation between the EMG sensor reading and the amount of force produced by the muscle. The third is to correlate the EMG sensor reading to the joint moments through inverse kinematics.

The first method for analyzing the muscle forces within a segment is to use mathematical modeling. This approach starts with a model of the segment of interest. The model includes the dimensions of the segments, their weights and centers of mass, the insertion points of the muscles, and physical properties such as ultimate strength. The greater the desired accuracy, the more complex the model becomes. Each muscle added to the model is another variable that must be found through the optimization. Once the
model is finished a set of mathematical equations and inequalities is constructed using the sum of all forces, the sum of all moments, and the constraints of muscle limitations. The last thing that is required is the optimization function. This is a function that relates everything to the final desired outcome, such as causing the minimum amount of compression on the joint, or creating the smallest possible joint moment to support the system. Finally, the equations are input into a computer and the computer run through various iterations of the equations making changes to the muscle force variables trying to find the combination of muscle forces that fulfills the optimization function. This method is good for getting an estimate of the individual muscle forces within a system, but requires time to develop the model and adapt it for each variation within a movement or activity. For rapid estimation and diagnosis of muscle activity and force, this is not always the best choice.

Another method for trying to analyze the muscle forces in a segment is to try to establish a direct relationship between the amount of activity measured through EMG sensors and the amount of force generated by the muscle. Studies in the past have tried to establish this relationship, but have been largely unsuccessful. In early works Inman et al tried came to several conclusions about the ability to relate muscle tension forces to the EMG signal amplitude. These include the idea that the integration of the EMG signal follows parallel to the magnitude of the tension force, that there is no quantitative relation between EMG and tension if the muscle is able to change length, that there is no quantitative relation between EMG and muscle power, that the EMG amplitude decreases as the muscles get stretched, and that there is a lag between the peak of the EMG and the peak of the muscle tension.[10] Other research has suggested that the main difficulties in
a direct relation come from the EMG sensors themselves. Because surface EMG sensors are often used, the ability to detect the signal from only the intended muscle gets diminished as the EMG picks up cross-talk from other muscle fibers, can only pick up the signals from a given region, and not from the entire muscle itself, and because of the involvement of other muscles that contribute to the movement.[11]

Because it is difficult to relate the activity measured through EMG directly to the force produced by a muscle, a third method for analysis can be used. This method of analysis correlates the resulting joint moments due to the muscles to the amount of activity recorded through the EMG sensors. Early studies had varying successes with the accuracy of joint moment predictions, but researchers believe this to be the method with the most promise.[12] Neural network algorithms have also been used in this approach to attempt to more accurately predict the joint moments during various movements. In order to relate the muscle activity measured through EMG to the joint moments kinematic data is required. This is often accomplished through the use of motion analysis software to get the locations and angles of each segment of interest. Motion analysis software is used to record and measure the angles and positions of the segments over time. Inverse kinematics can then be used to calculate the joint moments at each time, and recorded EMG data can then be related to these joint moments.
Chapter 2

Literature Review

Squatting is a task that is used to accomplish many daily activities, such as bending down to grab something, working on or near the ground, or just to relax and pass time, and can be performed with either the heels in contact with the ground, or lifted off of the ground.[3, 13, 14] Many of the previous studies have focused on the joint forces or moments for a single type of squatting position.[15-18] The effects of the position of the heels has not been largely studied, but some previous work has shown that the squatting with the heels off of the ground produces higher joint moments in the knee.[19, 20] Other studies have been done that show other deep knee flexion activities, such as kneeling, also affect the joint moments and stability after long periods of time.[21] Surveys have shown that the ability to perform squatting activities is listed as having a high importance within Asian populations affected by osteoarthritis.[22] A study done in Japan in 2013 showed that around 9% of people younger than 50 have knee osteoarthritis of some kind, and that it can increase to as much as 40% of people by their 70s.[23] The ability to
prevent osteoarthritis and restore motion after knee replacements may help in improving satisfaction within Asian cultures, as well as other populations that spend large amounts of time in a squatting position.[24]

There are many factors which play a role in the onset of osteoarthritis including age, diet, exercise, level of activity, previous injuries, genetics, and gender.[1, 19, 25-27] One study done by Driban et al. concluded that participation in sports such as soccer, distance running, and wrestling increased the odds of osteoarthritis of the knee joint by a factor between three and four, and that weight lifting specifically could increase the odds by a factor of seven.[1] In 2004 Ana Valdes et al. suggested that osteoarthritis onset and progression has a multigenic and feature-specific nature, and that further research into genetic markers could provide a reliable diagnosis for osteoarthritis. A study done by Ching-Heng Chou et al. in 2014 further backed up the claim that certain genetic factors could be used to identify patients with the potential for the progression of osteoarthritis due to the expression, or lack thereof, of certain genes.[26] Chou et al. found eight genes that were significantly linked to the progression of osteoarthritis within their tests volunteers. Obesity is another factor that has been shown to affect the risks of osteoarthritis, but is one that can be controlled through diet and exercise.[25, 28] Studies have also shown that comparisons between the Caucasians in the United States and Asian have a much higher rate of obesity in Caucasians.[29] Furthermore, it has been hypothesized that muscle strength can impact osteoarthritis progression, and that individuals with a higher BMI have lower muscle strengths when normalized.[28, 30, 31] Because the ligaments within the joints play a large role on the stability, any injuries can cause changes to the biomechanics and may lead to an increased risk of osteoarthritis.[32,
Diseases such as rheumatoid arthritis and gout can also play a role in the development of osteoarthritis, but have not been explored in great depth due to congenital joint deformities.[28, 34]

Many different techniques have been used to study the kinematics and kinetics of squatting in the past.[35-37] These methods include the traditional inverse kinematics and the more recent forward kinematics. Inverse kinematics uses anthropometric measures, ground reaction forces, kinematic data, and link analysis to determine the joint forces after the experiment has been run. Forward kinematics uses computer modeled bone segments and whole bodies to simulate the joint forces for verification with inverse kinematics. Recently these techniques have been used to study the daily activities of squatting, kneeling, and stair ascent and descent in greater detail.[21, 38-40] However, the majority of these studies have been on the biomechanics of the knee joint.[4, 14, 41, 42] Many papers have also looked at the muscle activities during daily activities and exercises to understand the role that the muscles play.[21, 43-46] No research could be found that looked into the effects of body weight shifting during the different squatting positions on the biomechanics of the ankles or the muscle activity in the lower leg.

**2.1 Purpose of Research**

Squatting is an activity that is used in the daily lives of many people. Many people engage in activities such as sports, gardening, passing time, or other activities that require squatting for prolonged periods of time. Most previous studies about squatting have been for either the weighted squat exercise or the body weight squat exercise, and few studies have been done over holding a squat position over prolonged periods. These
prolonged periods often cause the squatter to shift their weight to try to maintain comfort. This can put more stress on their joints as they move more of their body weight onto a single support leg, and because of this it is important to understand how the biomechanics may change as a person shifts their weight. Engaging in activities such as kneeling or squatting for long periods of time has been shown to increase the onset and progression of diseases such as osteoarthritis.

The purpose of this research is to perform a kinematic and EMG study to better understand the biomechanics of a deep squat as it affects the knee and ankle joints. This research is a continuation of a previous study to quantify the knee response during squats with heels up and down.[47] The differences between the previous research and the current study can be identified in the following table.

**Table 2-1 – Comparison of the aim of the current study to the previous study done at the University of Toledo**

<table>
<thead>
<tr>
<th>Kinematics and Kinetics of Both Knees During Various Squat Conditions</th>
<th>Previous Study[47]</th>
<th>Current Study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinematics of Both Knees During Asian Squat</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Kinematics of Both Knees During Catcher’s Squat</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Kinematics of Both Knees During Body Weight Shifting</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Compressive/Shear Forces at Knee Joint During all 4 Conditions</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Kinematics and Kinetics of Both Ankles During all 4 Conditions</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>EMG Activity of Ten Muscles within Both Legs During all 4 Conditions</td>
<td>No</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Chapter 3

Experimental Methods

The Biomechanics and Assistive Technology lab of the Department of Mechanical Engineering and Biomedical Engineering at the University of Toledo was used to conduct the tests. A ten camera motion analysis system from Motion Analysis, Inc. was used with reflective markers to record the motion data of the volunteers along with two force platforms from Advanced Mechanical Technology, Inc. used to record the ground reaction forces. Trigno wireless EMG sensors from Delsys, Inc. were used to collect EMG data from the quadriceps, hamstring, calf, and shin muscles. The software package Cortex from Motion Analysis, Inc. was used to collect and synchronize the data. The KinTools RT kit within Cortex was used along with Excel to refine and analyze the motion data, while EMGworks Analysis was used to refine and export the EMG data to Excel. Outputs such as knee moment, knee angle, ankle moment, ankle angle, and muscle activity as a percentage of the maximum voluntary contraction were found.
3.1 Test Protocol

A testing protocol was designed to collect biomechanics data from individuals performing various squatting activities. Each squatting activity was chosen to mimic the possible situations that an individual may experience if squatting is an activity that is regularly performed for longer periods of time. The testing protocol was approved by the Institutional Review Board at the University of Toledo (IRB#107636).

3.1.1 Materials and Equipment

Ten Raptor-E digital cameras from Motion Analysis, Inc. were used to capture the motion data at 120 Hz. Two Optima digital force platforms from Advanced Mechanical Technology, Inc. were used in conjunction with the cameras to collect ground reaction force data at 720 Hz. Reflective markers were placed on the surface of the skin in order to identify key landmarks of the body for motion analysis. EMG sensors from Delsys, Inc. were placed over four muscle groups on the legs to capture the muscle activity during the squatting activities at 720 Hz. Cortex software from Motion Analysis, Inc. was used to simultaneously collect the motion data from the cameras, the ground reaction forces from the force platforms, and the voltage data from the EMG sensors. KinTools RT software packaged within Cortex was used for motion analysis of the data to obtain the segment locations and joint moments.

3.1.2 Volunteer Group Demographic

Eight volunteers were recruited from the student population at the University of Toledo. Four males and four females volunteered for this experiment. The age of the male volunteers ranged from 19 to 27 years old, with an average age of 21.75 years. The
height of the male volunteers ranged from 69 to 73 inches, with an average height of 71.125 inches. The age of the female volunteers ranged from 19 to 23 years old, with an average age of 20.25 years. The height of the female volunteers ranged from 63 to 68.5 inches, with an average height of 66.188 inches. Before testing, each volunteer was given an explanation of the test, the risks, and the benefits in accordance with the IRB protocol. Each volunteer was then given a demonstration of the test and had the opportunity to ask questions before signing a consent form for participation in the study.

### 3.1.3 EMG Sensor Instrumentation

Ten EMG sensors were placed on each volunteer prior to testing. Each EMG sensor was placed over the body of the selected muscle as described by Basmajian.[48] One EMG sensor was placed on the rectus femoris, the biceps femoris, the tibialis anterior, the lateral head of the gastrocnemius, and the medial head of the gastrocnemius on both the right and left legs. Prior to EMG sensor placement each site was cleaned with a cotton swab and 70% isopropyl alcohol to remove any debris that may interfere with the EMG recordings. Each muscle was found by having the volunteer attempt to extend or flex the knee, or attempt to plantarflex or dorsiflex the foot in order to contract each muscle individually. The muscles were then inspected visually and through palpation to find the main body of the muscle.

Once the EMG sensors were placed over the body of the muscles a series of maximum voluntary contraction (MVC) tests were done for each muscle. These tests were done to get an average reading from each EMG sensor when the muscles were working at the maximum amount of voluntary contraction so that they could be used to normalize the readings from the squatting tests.
To get the average value from the biceps femoris the volunteer would lie on their stomach. The volunteer would then contract the biceps femoris by attempting to flex the knee while their leg was held in place by a large resistance. The MVC test was done three times, once with a starting knee flexion of 0°, once with a starting knee flexion of 30°, and once with a starting knee flexion of 60°. This was done so that one average value could be found over the normal range of motion.

To record the MVC tests for the rectus femoris the volunteer was seated in a chair. The volunteer would then contract the rectus femoris as hard as they could by trying to extend the knee while their leg was held in place by a large resistance. The MVC test was done three times, once with a starting knee flexion of 90°, once with a starting knee flexion of 60°, and once with a starting knee flexion of 30°.

To record the MVC tests for the tibialis anterior the volunteer was seated in a chair. The volunteer would then contract the tibialis anterior as hard as they could by trying to dorsiflex the ankle while their foot was held in place by a large resistance. The MVC test was done three times, once with a starting ankle flexion of 0°, once with a starting ankle plantarflexion of 30°, and once with a starting ankle dorsiflexion of 30°.

To record the MVC tests for the gastrocnemius the volunteer was standing with their knee resting on a chair. The volunteer would then contract the gastrocnemius as hard as they could by trying to plantarflex the ankle while their foot was held in place by a large resistance. The MVC test was done three times, once with a starting ankle flexion of 0°, once with a starting ankle plantarflexion of 30°, and once with a starting ankle dorsiflexion of 30°.
3.1.4 Reflective Marker Instrumentation

Once the MVC tests were finished the volunteers were instrumented with twenty-one reflective markers. These reflective markers were used to identify the key landmarks needed to reconstruct the lower half of the Helen-Hayes model used for motion analysis. One marker was placed on the right anterior-superior-iliac-spine (ASIS), the left ASIS, the sacrum, the lateral epicondyle of the right knee, the medial epicondyle of the right knee, the lateral malleolus of the right ankle, the medial malleolus of the right ankle, the calcaneus of the right foot, the 2nd metatarsal of the right foot, the lateral epicondyle of the left knee, the medial epicondyle of the left knee, the lateral malleolus of the left ankle, the medial malleolus of the left ankle, the calcaneus of the left foot, and the 2nd metatarsal of the left foot. One marker was also placed along the lateral side of the anterior of the thigh and the lateral side of the anterior of the shank for both the right and left foot. Additionally, one marker was placed on both the right and left greater trochanter in order to ensure that the virtual markers for the right and left hip calculated by Cortex were in line with the physical anatomy of the volunteer. The volunteers tucked in any loose clothing, and baggy shorts were taped up so that no markers would be covered up during motion. Figure 3-1 below shows the locations of the reflective markers and EMG sensors on a volunteer.
3.1.5 Static and Dynamic Tests

Once the markers and EMG sensors were placed on the volunteer a static test was done. The purpose of this test was to do get an average reading of the volunteer’s weight as it was measured by each force plate, as well as to give Cortex a set of reference frames to use as a template for creating the virtual markers and skeleton system for the Helen-Hayes marker set. The volunteer stood in front of the force platforms prior to beginning the recording. Once recording was started the volunteer was instructed to step onto the first force platform with both feet. The volunteer then remained stationary for two seconds to allow for a stable weight reading to be taken before being instructed to step over onto the other force platform with both feet. Finally the volunteer was instructed to step off of the second force platform after remaining stationary for two seconds. Once the
volunteer was off of the force platform the recording was stopped and the capture was loaded into Cortex’s post processing module. The markers were identified based on their locations and the virtual markers and skeleton system were created, allowing for real-time identification of the markers. The virtual markers were checked against the location of the two markers on the left and right greater trochanter to ensure that the virtual markers were calculated in an acceptable location. If they were not the location of the virtual markers was changed to better reflect the actual location of the volunteer’s greater trochanters, and the two markers on the greater trochanters were removed.

After the static test was done a second dynamic test was performed. During the dynamic test the volunteer had twenty seconds to move freely around the room as they chose. This was used to give Cortex a second set of extended data to use as reference for identifying the markers. Once the test was done the data were loaded in Cortex’s post processing module and the markers were checked for correct identification in each frame. Once all of the markers were correctly identified in every frame the template was extended to allow for more accurate identification of the markers in real time. Once the creation of the virtual markers and skeleton system were completed the medial markers on the right and left condyle and malleolus were removed.

### 3.1.6 Asian Squat Activity

After the static and dynamic tests were completed a series of squatting activities were performed. The volunteer stood off of the force platforms with one foot in front of each prior to recording. Once the recording started the volunteer was instructed to step onto the force platforms, putting one foot near the center of each platform. Once the volunteer reached a steady and stable standing position on the force platforms they were
given verbal instructions to perform a squat with their heels on the ground. The volunteer would then squat down as far as they could while maintaining contact between their heels and the ground, and then would rise back to a standing position in one motion. Once the volunteer returned to a steady and stable standing position they were given verbal instructions to step off of the force platforms. Once the volunteer was off of the force platforms the recording was stopped. After recording the volunteer was given some time to rest while the data were checked to ensure no markers were missing from the recording and that there were no errors with saving the analog data from the force platforms and the EMG sensors. The test was repeated until a total of five squatting tests were completed that had complete marker and analog data, without any unwanted events such as loss of balance.

3.1.7 Catcher Squat Activity

After performing the Asian squat activity a similar set of tests are performed. The volunteer stood off of the force platforms with one foot in front of each prior to recording. Once the recording started the volunteer was instructed to step onto the force platforms, putting one foot near the center of each platform. Once the volunteer reached a steady and stable standing position on the force platforms they were given verbal instructions to perform a squat with their heels off of the ground. The volunteer would then rise onto the balls of their feet as they squatted down as far as they could, and then would rise back to a standing position in one motion. Once the volunteer returned to a steady and stable standing position they were given verbal instructions to step off of the force platforms. Once the volunteer was off of the force platforms the recording was stopped. After recording the volunteer was given some time to rest while the data were
checked to ensure no markers were missing from the recording and that there were no errors with saving the analog data from the force platforms and the EMG sensors. The test was repeated until a total of five squatting tests were completed that had complete marker and analog data, without any unwanted events such as loss of balance.

3.1.8 Shifting Asian Squat Activity

After the catcher squat activity was performed the Asian squatting activity was repeated, but this time with the inclusion of body weight shifting. The volunteer stood off of the force platforms with one foot in front of each prior to recording. Once the recording started the volunteer was instructed to step onto the force platforms, putting one foot near the center of each platform. Once the volunteer reached a steady and stable standing position on the force platforms they were given verbal instructions to squat down with their heels on the ground. The volunteer would then squat down as far as they could while maintaining contact between their heels and the ground. Once the volunteer reached a stable position they were instructed to shift their weight onto their right leg. After shifting their weight as far as they were comfortable with they were instructed to shift their weight onto their left leg. After shifting their weight onto their left leg as much as they were comfortable with the volunteer was instructed to return to a neutral position with their weight evenly distributed between their legs. Once the volunteer evenly distributed weight they were instructed to return to a standing position. Once they returned to a steady and stable standing position they were given verbal instructions to step off of the force platforms. The recording was stopped after the volunteer was off of the force platforms. After recording the volunteer was given some time to rest while the data were checked to ensure no markers were missing from the recording and that there
were no errors with saving the analog data from the force platforms and the EMG sensors. The test was repeated until a total of five squatting tests were completed that had complete marker and analog data, without any unwanted events such as loss of balance.

3.1.9 Shifting Catcher Squat Activity

After the shifting Asian squat activity was performed the shifting catcher squatting activity was performed. The volunteer stood off of the force platforms with one foot in front of each prior to recording. Once the recording started the volunteer was instructed to step onto the force platforms, putting one foot near the center of each platform. Once the volunteer reached a steady and stable standing position on the force platforms they were given verbal instructions to squat down with their heels on the ground. The volunteer would then squat down as far as they could while maintaining contact between their heels and the ground. Once the volunteer reached a stable position they were instructed to shift their weight onto their right leg. After shifting their weight as far as they were comfortable with they were instructed to shift their weight onto their left leg. After shifting their weight onto their left leg as much as they were comfortable with the volunteer was instructed to return to a neutral position with their weight evenly distributed between their legs. Once the volunteer evenly distributed weight they were instructed to return to a standing position. Once they returned to a steady and stable standing position they were given verbal instructions to step off of the force platforms. The recording was stopped after the volunteer was off of the force platforms. After recording the volunteer was given some time to rest while the data were checked to ensure no markers were missing from the recording and that there were no errors with saving the analog data from the force platforms and the EMG sensors. The test was
repeated until a total of five squatting tests were completed that had complete marker and analog data, without any unwanted events such as loss of balance.

3.2 Data Processing

After the tests were performed the data had to be processed. Each test was trimmed to include only the data from the time right before the volunteer began the descent phase of the squat up until the time right after the volunteer completed the ascent phase of the squat. The trimmed captures were then inspected to ensure that no markers were missing during the trial. The marker data was then filtered using the post processing tools inside of Cortex. A Butterworth filter with a cut off frequency of 6 Hz was applied to the marker data.

3.2.1 Motion Analysis

After processing the data from each recording, the KinTools RT toolset within the Cortex software was used to obtain the joint angles and moments from the marker and force platform data. The markers on the body were used to calculate the joint centers based on anthropomorphic data within the Cortex software. The markers on the left and right greater trochanter were used to ensure that the virtual markers created for the left and right hip were in line with the anatomically determined hip positions. The proximal end of the thigh segment was defined as the virtual marker for the joint center of the hip, and the distal end was defined as the virtual marker for the joint center of the knee. The marker on the lateral side of the anterior of the thigh was used to keep track of the thigh segment’s rotation. The proximal end of the shank segment was defined as the virtual marker for the joint center of the knee, and the distal end was defined as the virtual
marker for the joint center of the ankle. The marker on the lateral side of the anterior of the shank was used to keep track of the shank segment’s rotation. The proximal end of the foot segment was defined as the virtual marker for the joint center of the ankle, and the distal end was defined as the marker placed on the 2\(^{nd}\) metatarsal. The marker on the lateral malleolus was used to keep track of the segment’s rotation. Once the segments were defined KinTools RT was used to calculate joint angles and moments from the marker and force platform data, and the data were exported to Excel for further analysis. The processed force platform ground reaction forces and EMG signals were also exported to Excel for further analysis.

3.2.2 EMG Preparation

The EMG signals in Excel were trimmed so that only the channels containing the processed data from the ten EMG sensors used were kept. The trimmed data were then imported into EMGWorks Analysis from Delsys® Inc. The data were then filtered using a 2\(^{nd}\) order Butterworth bandpass filter with a lower cut off frequency of 20 Hz and a higher cut off frequency of 355 Hz. After filtering, the linear envelope for each trial was found using the root-mean-square method with a window length of 0.125 seconds and an overlap of 0.0625 seconds. Finally the trials were exported back into Excel for further analysis.

3.2.3 EMG and Force Platform Analysis

The MVC trials were used to find the average maximum voluntary muscle activity for each muscle in each position, and to find the average maximum voluntary muscle activity over the range of motion for each muscle. Once the average maximum
voluntary muscle activity for each muscle was found, the other trials were all normalized
with respect to the individual muscles’ maximum. The force platform data from the static
test was also used to find a body weight reading for the volunteers as measured by the
individual force platforms. The weights were then used to normalize the individual joint
moments to the volunteer’s mass. The time of the squatting activity was also normalized
by the time it took to perform the entire activity in order to compare the volunteers to
each other based on the percentage of the squatting activity completed.
Chapter 4

Results

4.1 Knee Joint Kinetics

4.1.1 Knee Joint Flexion-Extension Moments

Knee joint flexion and extension moments for the squat then stand trials saw a similar trend among all volunteers in the experiment. Furthermore, the general trend occurred when squatting with the heels on the ground and with the heels off of the ground. The squatting motion generally started with a small flexion moment (between 0.05 and 0.10 Nm/kg) when the knee angle was between 0° and 10° of flexion. As the knee flexion angle continued to increase from 0° to 10° the flexion moment decreased. Past 10° of knee flexion the knee joint moment switched to an extension moment which continued to increase as the knee flexion angle increased. On average for the right leg the peak knee extension moment was 0.711 Nm/kg for the Asian squat and 0.832 Nm/kg for the Catcher's squat. The peak knee flexion angle was 123.6° during the Asian squat and
132.6° for the Catcher's squat. The time it took to load the knee joint differed between the Asian squat and the Catcher's squat. The Asian squat reached 50% of its maximum knee joint moment after reaching 27% of the maximum knee flexion angle, and it reached 90% of its maximum knee joint moment after reaching 67% of the maximum knee flexion angle. The Catcher's squat reached 50% of its maximum knee joint moment after reaching 47% of its maximum knee flexion angle, and it reached 90% of its maximum knee joint moment after reaching 79% of its maximum knee flexion angle. The right and left legs both showed a similar trend, but the left leg had consistently smaller knee extension moments. The left leg reached an average peak knee extension moment of 0.609 Nm/kg and an average peak knee flexion angle of 118.8° for the Asian squat. For the Catcher's squat the left leg reached an average peak knee extension moment of 0.773 Nm/kg and an average peak knee flexion angle of 128.9°.

Figure 4-1 – The average knee extension moment for all volunteers during the Asian squat
4.1.2 Knee Joint Flexion-Extension Moments of Shifting Squats

The joint flexion and extension moments for the squat with weight shifting showed trends similar to those in the squat then stand trials. Before shifting body weight the right leg of the Asian squat reached an average knee extension moment of 0.728 Nm/kg with a knee flexion angle of 102.8°. During body weight shifting the Asian squat reached a peak knee joint moment of 0.951 Nm/kg and a peak knee flexion angle of 121.8°. This equates to a 30.6% increase in the knee joint moment and an increase of 18.5% in the knee flexion angle due to weight shifting. Before shifting body weight the Catcher's squat reached an average knee extension moment of 0.747 Nm/kg with a knee flexion angle of 112.6°. During body weight shifting the Catcher’s squat reached a peak knee extension moment of 1.255 Nm/kg and a peak knee flexion angle of 132.9°. This equates to an increase of 68.0% in the knee extension moment and an increase of 18.0% in the knee flexion angle due to body weight shifting. The Catcher's squat also caused an
increase of 32.0% in the knee extension moment and an increase of 9.1% in the knee flexion angle as compared to the Asian squat. The left leg had similar trends to the right leg but with smaller values.

Figure 4-3 – The average knee extension moments for all volunteers during the Asian squat with weight shifting

Figure 4-4 – The average knee extension moments for all volunteers during the Catcher’s squat with weight shifting
4.1.3 Comparison of Knee Joint Flexion-Extension Moments

While the male and female volunteers both followed the same general trends when performing the squatting exercises, they had different results. In general, the male volunteers had greater knee flexion angles than the female volunteers, but they had smaller knee extension moments than the female volunteers. For the Asian squats male volunteers reached an average peak knee extension moment of 0.798 Nm/kg and an average peak knee flexion angle of 131.0°. The female volunteers reached an average peak knee extension moment of 0.624 Nm/kg and an average peak knee flexion angle of 116.2°. Weight shifting increased the male volunteers' average peak knee extension moment to 1.013 Nm/kg and decreased the average peak knee flexion angle to 130.5°. It also increased the female volunteers' average peak knee extension moment to 0.888 Nm/kg and decreased the average peak knee flexion angle to 113.1°. For the Catcher's squats male volunteers reached an average peak knee extension moment of 0.870 Nm/kg and an average peak knee flexion angle of 136.9°. The female volunteers reached an average peak knee extension moment of 0.794 Nm/kg and an average peak knee flexion angle of 128.4°. Weight shifting increased the male volunteers' average peak knee extension moment to 1.374 Nm/kg and decreased the average peak knee flexion angle to 136.3°. It also increased the female volunteers' average peak knee extension moment to 1.137 Nm/kg and the average peak knee flexion angle to 129.5°.
Figure 4-5 – The average knee extension moment for the male volunteers during the Asian squat

Figure 4-6 – The average knee extension moment for the male volunteers during the Catcher’s squat
Figure 4-7 – The average knee extension moment for the female volunteers during the Asian squat

Figure 4-8 – The average knee extension moment for the female volunteers during the Catcher’s squat
4.2 Ankle Joint Kinetics

4.2.1 Ankle Joint Plantarflexion Moments

Ankle joint plantarflexion and dorsiflexion moments for the squat then stand trials saw a similar trend among all volunteers in the experiment. However, the general trend when squatting with the heels on the ground and with the heels off of the ground were very different. The ankle angle generally started in a plantarflexed position. Once the squatting activity started the ankle angle would decrease in plantarflexion angle, and then switch to an increasing dorsiflexion angle. During the Asian squats, as the ankle angle became more neutral (less plantarflexion or less dorsiflexion) the ankle joint plantarflexion moment decreased. During the Catcher’s squats, the ankle joint plantarflexion moment increased when the heels were lifted off of the ground and then remained that way until the heels were placed back onto the ground. On average for the right leg the peak ankle plantarflexion moment was 0.239 Nm/kg for the Asian squat, and 0.539 Nm/kg for the Catcher's squat. This equates to a 125% increase in ankle plantarflexion moments on average due to lifting the heels off of the ground. The peak ankle plantarflexion angle was 15.7° and the peak ankle dorsiflexion angle was 10.65° during the Asian squat. The peak ankle plantarflexion angle was 15.6° and the peak ankle dorsiflexion angle was 8.29° during the Catcher's squat. The right and left legs both showed a similar trend, but the left leg tended to have higher values. The left leg reached an average peak ankle plantarflexion moment of 0.279 Nm/kg for the Asian squat, and a peak ankle plantarflexion moment of 0.553 Nm/kg for the Catcher's squat. The average peak ankle plantarflexion angle of the left leg reached 16.3° for the Asian squat and a
peak of 17.8° for the Catcher’s squat. The average peak ankle dorsiflexion angle of the left leg reached 10.5° for the Asian squat and a peak of 9.4° for the Catcher's squat.

Figure 4-9 – The average ankle plantarflexion moments for all volunteers during the Asian squat

Figure 4-10 – The average ankle plantarflexion moments for all volunteers during the Catcher’s squat
4.2.2 Ankle Joint Plantarflexion Moments for Shifting Squats

Ankle joint plantarflexion and dorsiflexion moments for the squat with weight shifting trials showed a similar trend to the squat then stand trials. On average for the right leg the peak ankle plantarflexion moment was 0.531 Nm/kg for the Asian squat, and 0.691 Nm/kg for the Catcher's squat. This equates to a 30.1% increase in ankle plantarflexion moments on average due to lifting the heels off of the ground. The peak ankle plantarflexion angle was 14.6° and the peak ankle dorsiflexion angle was 16.4° during the Asian squat. The peak ankle plantarflexion angle was 18.0° and the peak ankle dorsiflexion angle was 10.9° during the Catcher's squat. The right and left legs both showed a similar trend, but the left leg tended to have higher values. The left leg reached an average peak ankle plantarflexion moment of 0.594 Nm/kg for the Asian squat, and a peak ankle plantarflexion moment of 0.742 Nm/kg for the Catcher's squat. The average peak ankle plantarflexion angle of the left leg reached 15.4° for the Asian squat and a peak of 18.1° for the Catcher's squat. The average peak ankle dorsiflexion angle of the left leg reached 17.4° for the Asian squat and a peak of 12.5° for the Catcher's squat.
4.2.3 Comparison of Ankle Joint Plantarflexion Moments

The male and female volunteers both followed the same general trends when performing the squatting exercises, but the females tended to have greater ankle
plantarflexion moments. For the Asian squat male volunteers reached an average peak ankle plantarflexion moment of 0.204 Nm/kg, an average peak ankle planterflexion angle of 15.4°, and an average peak ankle dorsiflexion angle of 10.3°. The female volunteers reached an average peak ankle plantarflexion moment of 0.274 Nm/kg, an average peak ankle planterflexion angle of 15.9°, and an average peak ankle dorsiflexion angle of 11.0°. This is a decrease for the male volunteers of 25.5% in the ankle plantarflexion moment when compared to the female volunteers. Weight shifting increased the male volunteers' average peak ankle plantarflexion moment to 0.487 Nm/kg, decreased the average peak ankle planterflexion angle to 14.7°, and increased the average peak ankle dorsiflexion angle to 15.3°. It also increased the female volunteers' average peak ankle plantarflexion moment to 0.575 Nm/kg, decreased the average peak ankle planterflexion angle to 14.6°, and increased the average peak ankle dorsiflexion angle to 17.4°. This is a decrease for the male volunteers of 15.3% in the ankle plantarflexion moment when compared to the female volunteers. For the Catcher's squat male volunteers reached an average peak ankle plantarflexion moment of 0.561 Nm/kg, an average peak ankle planterflexion angle of 17.6°, and an average peak ankle dorsiflexion angle of 5.8°. The female volunteers reached an average peak ankle plantarflexion moment of 0.517 Nm/kg, an average peak ankle planterflexion angle of 13.5°, and an average peak ankle dorsiflexion angle of 10.8°. This is a increase for the male volunteers of 8.5% in the ankle plantarflexion moment when compared to the female volunteers. Weight shifting increased the male volunteers' average peak ankle plantarflexion moment to 0.660 Nm/kg, the average peak ankle plantarflexion angle to 22.3°, and the average peak ankle dorsiflexion angle to 7.5°. It also increased the female volunteers' average peak ankle
plantarflexion moment to 0.721 Nm/kg, the average peak ankle plantarflexion angle to 13.8°, and the average peak ankle dorsiflexion angle to 14.3°. This is a decrease for the male volunteers of 8.5% in the ankle plantarflexion moment when compared to the female volunteers.

Figure 4-13 – The average ankle plantarflexion moments for the male volunteers during the Asian squat

Figure 4-14 – The average ankle plantarflexion moments for the male volunteers during the Catcher’s squat
Figure 4-15 – The average ankle plantarflexion moments for the female volunteers during the Asian squat

Figure 4-16 – The average ankle plantarflexion moments for the female volunteers during the Asian squat
4.3 Muscle Activities

4.3.1 Quadriceps Activities

The quadriceps muscles showed varying degrees of activity throughout the squatting activities. The activity generally increased as the knee flexion angle increased. During the Asian squat the peak activity for the average of all volunteers was 104.9% of the maximum voluntary contraction for the right leg and 116.0% for the left leg. During the Catcher's Squat the peak activity for the average of all volunteers was 83.7% for the right leg and 98.8% for the left leg. This equates to a decrease of 20.2% of muscle activity in the right leg and a decrease of 14.8% in the left leg due to lifting the heels off of the ground. Body weight shifting increased the muscle activity during the Asian squat to 134.2% in the right leg and 141.0% in the left leg. This is an increase of 27.9% in the right leg and 21.5% in the left leg compared to the non-weight shifting case. Body weight shifting also increased the muscle activity during the Catcher's squat to 104.5% in the right leg and 139.6% in the left leg. This is an increase of 24.9% in the right leg and 41.3% in the left leg.
Figure 4-17 – The muscle activities (as a percentage of the maximum voluntary contraction) of the hamstrings and quadriceps muscle groups on the right and left leg for all volunteers during the Asian squat.

Male and female volunteers both showed the same trend in muscle activity during the squatting exercises, but had different results. During the Asian squat the peak activity for the male volunteers was 82.7% for the right leg and 73.1% for the left leg. The female volunteers reached a peak of 121.7% for the right leg and 158.8% for the left leg. During

Figure 4-18 – The muscle activities (as a percentage of the maximum voluntary contraction) of the hamstrings and quadriceps muscle groups on the right and left leg for all volunteers during the Catcher’ squat.

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the Catcher's Squat the peak activity for the male volunteers was 55.2% for the right leg and 52.2% for the left leg. The female volunteers reached a peak of 112.3% for the right leg and 133.8% for the left leg. Body weight shifting increased the muscle activity during the Asian squat for the male volunteers to a peak of 108.8% in the right leg and 75.7% in the left leg. The female volunteers reached a peak of 159.6% in the right leg and 206.3% in the left leg during the Asian squat with body weight shifting. The muscle activity during the Catcher's squat was also increased in the male and female volunteers due to body weight shifting. The male volunteers reached a peak of 67.2% in the right leg and 77.6% in the left leg. The female volunteers reached a peak muscle activity of 141.8% in the right leg and 195.6% in the left leg.

![Male Average Asian EMGs](image)

**Figure 4-19** – The muscle activities (as a percentage of the maximum voluntary contraction) of the hamstrings and quadriceps muscle groups on the right and left leg for the male volunteers during the Asian squat
**Figure 4-20** – The muscle activities (as a percentage of the maximum voluntary contraction) of the hamstrings and quadriceps muscle groups on the right and left leg for the male volunteers during the Catcher’s squat.

**Figure 4-21** – The muscle activities (as a percentage of the maximum voluntary contraction) of the hamstrings and quadriceps muscle groups on the right and left leg for the female volunteers during the Asian squat.
4.3.2 Hamstrings Activities

Hamstring activity was relatively quiet throughout all squatting activities. During the Asian squat the average activity for the average of all volunteers was 7.3% of the maximum voluntary contraction with a peak of 14.4% for the right leg and an average of 6.2% with a peak of 11.3% for the left leg. During the Catcher's Squat the average activity for the average of all volunteers was 7.3% with a peak of 19.8% for the right leg and an average 6.7% with a peak of 12.6% for the left leg. This results in no change to the average muscle activity in the right leg and an increase of 8.1% in the left leg due to lifting the heels off of the ground. Body weight shifting increased muscle activity during the Asian squat to an average of 7.3% with a peak of 14.5% in the right leg and an average of 6.5% with a peak of 15.0% in the left leg. Body weight shifting decreased the average, but increased the peak muscle activity during the Catcher's squat to an average
of 5.9% with a peak of 12.6% in the right leg and an average of 6.6% with a peak of 18.9% in the left leg.

Male and female volunteers both showed the same trend in muscle activity during the squatting exercises, but had different results. During the Asian squat the average activity for the male volunteers was 4.7% with a peak of 10.0% for the right leg and an average of 5.2% with a peak of 10.8% for the left leg. The female volunteers reached an average of 9.8% with a peak of 18.7% for the right leg and an average of 7.3% with a peak of 11.9% for the left leg. During the Catcher's Squat the average activity for the male volunteers was 5.5% with a peak of 12.3% for the right leg and an average of 6.6% with a peak of 12.9% for the left leg. The female volunteers reached an average of 9.0% with a peak of 27.3% for the right leg and an average of 6.7% with a peak of 12.2% for the left leg. During the Asian squat for the male volunteers, body weight shifting decreased the average muscle activity to 4.6% while increasing the peak to 11.3% in the right leg, and decreased the average to 5.2% while increasing the peak to 15.3% in the left leg. The female volunteers reached an average of 10.1% with a peak of 17.6% in the right leg and 7.8% with a peak of 14.7% in the left leg during the Asian squat with body weight shifting. The muscle activity during the Catcher's squat was also changed in the male and female volunteers due to body weight shifting. The male volunteers reached an average of 5.0% with a peak of 12.6% in the right leg and an average of 7.2% with a peak of 15.4% in the left leg. The female volunteers reached an average muscle activity of 6.9% with a peak of 12.6% in the right leg and an average of 6.0% with a peak of 22.4% in the left leg.
4.3.3 Tibialis Anterior Activities

The tibialis anterior muscles showed varying degrees of activity throughout the squatting activities. The activity generally increased as the knee flexion angle increased. During the Asian squat the peak activity for the average of all volunteers was 121.3% of the maximum voluntary contraction for the right leg and 124.4% for the left leg. During the Catcher's Squat the average activity for the average of all volunteers was 48.8% for the right leg and 56.6% for the left leg. This equates to a decrease of 40.2% in muscle activity in the right leg and a decrease of 45.5% in the left leg due to lifting the heels off of the ground. Body weight shifting decreased the muscle activity during the Asian squat to 113.3% in the right leg and 109.0% in the left leg. This is a decrease of 6.6% in the right leg and 12.4% in the left leg compared to the non-weight shifting case. Body weight shifting increased the muscle activity during the Catcher's squat to 63.9% in the right leg and 65.6% in the left leg. This is an increase of 30.9% in the right leg and 15.9% in the left leg.
Male and female volunteers both showed the same trend in muscle activity during the squatting exercises, but had different results. During the Asian squat the peak activity for the male volunteers was 85.2% for the right leg and 151.7% for the left leg. The female volunteers reached a peak of 157.4% for the right leg and 97.1% for the left leg.
During the Catcher's Squat the peak activity for the male volunteers was 38.8% for the right leg and 78.6% for the left leg. The female volunteers reached a peak of 58.8% for the right leg and 34.7% for the left leg. Body weight shifting decreased the muscle activity during the Asian squat for the male volunteers to a peak of 75.2% in the right leg and 129.6% in the left leg. The female volunteers reached a peak of 151.3% in the right leg and 88.4% in the left leg during the Asian squat with body weight shifting. The muscle activity during the Catcher's squat was increased in the male and female volunteers due to body weight shifting. The male volunteers reached a peak of 40.8% in the right leg and 77.6% in the left leg. The female volunteers reached a peak muscle activity of 87.0% in the right leg and 53.6% in the left leg.

Figure 4-25 – The muscle activities (as a percentage of the maximum voluntary contraction) of the tibialis anterior muscle group on the right and left leg for the male volunteers during the Asian squat
Figure 4-26 – The muscle activities (as a percentage of the maximum voluntary contraction) of the tibialis anterior muscle group on the right and left leg for the male volunteers during the Catcher’s squat.

Figure 4-27 – The muscle activities (as a percentage of the maximum voluntary contraction) of the tibialis anterior muscle group on the right and left leg for the female volunteers during the Asian squat.
4.3.4 Gastrocnemius Activities

Gastrocnemius activity was relatively unchanged throughout all Asian squatting activities. There were some slight fluctuations caused from maintaining balance, but there were no parts of the squat with a consistent change in activity. During the Catcher’s squats the gastrocnemius activities all increased as the heels were lifted off of the ground, and then remained relatively unchanged until the heels were placed on the ground again. After looking at the individual Gastrocnemius activities it became clear that there was a problem with Volunteer 7’s right lateral gastrocnemius during the Asian squat with weight shifting, as well as having a problem with Volunteer 3’s left lateral gastrocnemius during both weight shifting squats. This problem may have been caused by an issue with the sensors being bumped during the shifting trials or losing adhesion even after checking the sensors before each set of trials.
Figure 4-29 – The muscle activities (as a percentage of the maximum voluntary contraction) of both heads of the gastrocnemius muscle groups on the right and left leg for all volunteers during the Asian squat

Figure 4-30 – The muscle activities (as a percentage of the maximum voluntary contraction) of both heads of the gastrocnemius muscle groups on the right and left leg for all volunteers during the Catcher’s squat
Figure 4-31 – The muscle activities (as a percentage of the maximum voluntary contraction) of both heads of the gastrocnemius muscle groups on the right and left leg for the male volunteers during the Asian squat.

Figure 4-32 – The muscle activities (as a percentage of the maximum voluntary contraction) of both heads of the gastrocnemius muscle groups on the right and left leg for the male volunteers during the Catcher’s squat.
4.3.4.1 Medial Gastrocnemius Activities

During the Asian squat the muscle activity for the average of all volunteers was on average 31.2% of the maximum voluntary contraction with a peak of 63.8% for the right leg and an average of 26.0% with a peak of 54.4% for the left leg. During the
Catcher's Squat the muscle activity for the average of all volunteers was on average 56.9% with a peak of 120.9% for the right leg and on average 53.9% with a peak of 131.9% for the left leg. This equates to an increase of 82.4% in the average muscle activity in the right leg and an increase of 107.3% in the left leg due to lifting the heels off of the ground. Body weight shifting increased the muscle activity during the Asian squat to an average of 29.1% with a peak of 68.3% in the right leg and an average of 34.5% with a peak of 122.1% in the left leg. This is a decrease of 6.7% in the average muscle activity of the right leg and an increase of 32.6% in the left leg compared to the non-weight shifting case. Body weight shifting also decreased the muscle activity during the Catcher's squat to an average of 45.8% with a peak of 155.1% in the right leg and an average of 50.4% with a peak of 217.7% in the left leg. This is a decrease of 19.5% in the average muscle activity of right leg and a decrease of 6.5% in the left leg due to body weight shifting.

Male and female volunteers both showed the same trend in muscle activity during the squatting exercises, but had different results. During the Asian squat the activity for the male volunteers was on average 21.8% with a peak of 56.6% for the right leg and on average 17.3% with a peak of 43.1% for the left leg. The female volunteers were on average 40.5% with a peak of 70.9% for the right leg and on average 34.6% with a peak of 65.8% for the left leg. During the Catcher's Squat the activity for the male volunteers was on average 47.2% with a peak of 98.5% for the right leg and on average 43.8% with a peak of 128.6% for the left leg. The female volunteers were on average 66.5% with a peak of 143.2% for the right leg and on average 67.3% with a peak of 136.2% for the left leg. Body weight shifting changed the muscle activity during the Asian squat for the male
volunteers to an average of 20.9% with a peak of 53.1% in the right leg and on average of 21.6% with a peak of 111.2% in the left leg. The female volunteers had an average activity of 37.2% with a peak of 83.5% in the right leg and on average 47.5% with a peak of 132.9% in the left leg during the Asian squat with body weight shifting. The muscle activity during the Catcher's squat was decreased in the male and female volunteers due to body weight shifting. The male volunteers had an average activity of 35.9% with a peak of 109.3% in the right leg and an average of 39.7% with a peak of 145.9% in the left leg. The female volunteers had an average muscle activity of 55.7% with a peak of 201.0% in the right leg and an average of 61.2% with a peak of 289.4% in the left leg.

4.3.4.2 Lateral Gastrocnemius Activities

During the Asian squat the average activity for the average of all volunteers was 18.9% of the maximum voluntary contraction with a peak of 33.8% for the right leg and an average of 22.8% with a peak of 43.2% for the left leg. During the Catcher's Squat the average activity for the average of all volunteers was 28.3% with a peak of 57.5% for the right leg and an average of 44.0% with a peak of 87.9% for the left leg. This equates to an increase of 49.7% in average muscle activity in the right leg and an increase of 93.0% in the left leg due to lifting the heels off of the ground. Body weight shifting increased the muscle activity during the Asian squat to an average of 19.3% with a peak of 40.1% in the right leg and an average of 23.4% with a peak of 65.2% in the left leg. Body weight shifting decreased the muscle activity during the Catcher's squat to an average of 25.8% with a peak of 62.9% in the right leg and an average of 29.3% with a peak of 63.1% in the left leg.
Male and female volunteers both showed the same trend in muscle activity during the squatting exercises, but had different results. During the Asian squat the average activity for the male volunteers was 17.5% with a peak of 39.0% for the right leg and an average of 17.0% with a peak of 45.3% for the left leg. The female volunteers had an average activity of 20.2% with a peak of 28.5% for the right leg and an average of 28.6% with a peak of 41.1% for the left leg. During the Catcher's Squat the muscle activity for the male volunteers was on average 24.2% with a peak of 45.5% for the right leg and on average 38.5% with a peak of 79.6% for the left leg. The female volunteers had an average activity of 31.3% with a peak of 66.5% for the right leg and an average of 49.6% with a peak of 96.1% for the left leg. Body weight shifting changed the muscle activity during the Asian squat for the male volunteers to an average of 14.4% with a peak of 34.0% in the right leg and an average of 22.5% with a peak of 80.4% in the left leg. The female volunteers had an average activity of 23.0% with a peak of 44.6% in the right leg and an average of 24.6% with a peak of 45.0% in the left leg during the Asian squat with body weight shifting. The muscle activity during the Catcher's squat was changed in the male and female volunteers due to body weight shifting. The male volunteers had an average activity of 25.7% with a peak of 62.7% in the right leg and an average of 30.5% with a peak of 69.5% in the left leg. The female volunteers had an average muscle activity of 26.0% with a peak of 63.1% in the right leg and an average muscle activity of 27.7% with a peak of 54.6% in the left leg.
4.4 Ground Reaction Forces

4.4.1 Ground Reaction Forces during Squats

The vertical ground reaction forces saw a similar trend for both the Asian and Catcher’s squats. During the beginning of the descent phase and the ending of the ascent phase of the squat the vertical ground reaction force decreased slightly. During the end of the descent phase and the beginning of the ascent phase of the squat the ground reaction forces increased. During both the Asian and Catcher’s squats the right leg had more vertical force than the left leg during the entire activity. During the Asian squat the average maximum vertical ground reaction forces for all volunteers were 0.566 N/N on the right leg and 0.533 N/N on the left leg. There were two instances where greater vertical forces occurred simultaneously in the left and right leg. The first was when force was required to stop the descent phase of the squat, and the second was when more force was required to start the ascent phase of the squat. The force required to start the ascent phase of the squat was the greatest vertical reaction force recorded. During the Catcher’s squat the average maximum vertical ground reaction forces for all volunteers were 0.556 N/N on the right leg and 0.537 N/N on the left leg. The force required to start the ascent phase of the squat was the greatest vertical reaction force recorded. This is a decrease of 1.8% in the ground reaction force of the right leg when compared to the Asian squat, and an increase of 0.8% in the ground reaction force of the left leg when compared to the Asian squat. The vertical ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-35 and Figure 4-36.
The medial and lateral ground reaction forces saw a similar trend for both the Asian and Catcher’s squats. Before beginning of the squat and after the squat the ground reaction forces on the volunteer were medial. As the volunteers descended the ground reaction forces on the volunteer become more lateral. During the Asian squat the ground reaction forces switched from medial to lateral during the squatting activity, but during
the Catcher’s squat the ground reaction force remained medial during the entire activity. During the Asian squat the average maximum medial ground reaction forces for all volunteers were 0.059 N/N on the right leg and 0.050 N/N on the left leg. During the Asian squat the average maximum lateral ground reaction forces for all volunteers were 0.019 N/N on the right leg and 0.026 N/N on the left leg. During the Catcher’s squat the average maximum medial ground reaction forces for all volunteers were 0.065 N/N on the right leg and 0.058 N/N on the left leg. This is an increase of 10.2% in the medial ground reaction force of the right leg when compared to the Asian squat, and an increase of 16.0% in the medial ground reaction force of the left leg when compared to the Asian squat. During the Catcher’s squat the average minimum medial ground reaction forces for all volunteers were 0.026 N/N on the right leg and 0.019 N/N on the left leg. This is a decrease of 236.8% in the lateral ground reaction force of the right leg when compared to the Asian squat, and a decrease of 173.1% in the lateral ground reaction force of the left leg when compared to the Asian squat. The medial-lateral ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-37 and Figure 4-38.
The anterior and posterior ground reaction forces saw a different trend for the Asian and Catcher’s squats. During the Asian squat the ground reaction force became more anterior during the beginning portion of the descent and ascent phases. During the Catcher’s squat the ground reaction force became more posterior during the descent phase and more anterior during the ascent phase. During the Asian squat the average
maximum anterior ground reaction forces for all volunteers were 0.009 N/N on the right leg and 0.008 N/N on the left leg. During the Asian squat the average maximum posterior ground reaction forces for all volunteers were 0.003 N/N on the right leg and 0.005 N/N on the left leg. During the Catcher’s squat the average maximum anterior ground reaction forces for all volunteers were 0.012 N/N on the right leg and 0.017 N/N on the left leg. This is an increase of 33.3% in the anterior ground reaction force of the right leg when compared to the Asian squat, and an increase of 112.5% in the anterior ground reaction force of the left leg when compared to the Asian squat. During the Catcher’s squat the average maximum posterior ground reaction forces for all volunteers were 0.009 N/N on the right leg and 0.004 N/N on the left leg. This is an increase of 200.0% in the posterior ground reaction force of the right leg when compared to the Asian squat, and a decrease of 20.0% in the lateral ground reaction force of the left leg when compared to the Asian squat. The anterior-posterior ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-39 and Figure 4-40.
4.4.2 Ground Reaction Forces during Squats with Weight Shifting

The vertical ground reaction forces saw a similar trend for both the Asian and Catcher’s squats with weight shifting. During the beginning of the descent phase and the ending of the ascent phase of the squat the vertical ground reaction force decreased slightly. During the end of the descent phase and the beginning of the ascent phase of the
squat the ground reaction forces increased. When the volunteer shifted weight to the right leg the vertical ground reaction force of the right leg increased while the ground reaction force of the left leg decreased. When the volunteer shifted weight to the left leg the vertical ground reaction force of the left leg increased while the ground reaction force of the right leg decreased. During both the Asian and Catcher’s squats the right leg had more vertical force than the left leg. During the Asian squat the average maximum vertical ground reaction forces for all volunteers were 0.808 N/N on the right leg and 0.791 N/N on the left leg. This is an increase of 42.8% in the ground reaction force of the right leg when compared to the non-weight shifting case, and an increase of 48.4% in the ground reaction force of the left leg when compared to the non-weight shifting case. During the Catcher’s squat the average maximum vertical ground reaction forces for all volunteers were 0.814 N/N on the right leg and 0.795 N/N on the left leg. This is an increase of 42.8% in the ground reaction force of the right leg when compared to the non-weight shifting case, and an increase of 48.4% in the ground reaction force of the left leg when compared to the non-weight shifting case. The vertical ground reaction forces for the Asian and Catcher’s squats with weight shifting can be seen below in Figure 4-41 and Figure 4-42.
The medial and lateral ground reaction forces saw a similar trend for both the Asian and Catcher’s squats with weight shifting. Before beginning of the squat and after the squat the ground reaction forces on the volunteer were medial. As the volunteers descended the ground reaction forces on the volunteer become more lateral. As the volunteer shifted weight onto one leg the ground reaction force on that same leg become...
more lateral, while the ground reaction force on the other leg became more medial. During the Asian squat with weight shifting the average maximum medial ground reaction forces for all volunteers were 0.061 N/N on the right leg and 0.055 N/N on the left leg. During the Asian squat with weight shifting the average maximum lateral ground reaction forces for all volunteers were 0.009 N/N on the right leg and 0.012 N/N on the left leg. During the Catcher’s squat with weight shifting the average maximum medial ground reaction forces for all volunteers were 0.071 N/N on the right leg and 0.061 N/N on the left leg. During the Catcher’s squat the average maximum lateral ground reaction forces for all volunteers were -0.005 N/N on the right leg and 0.003 N/N on the left leg. The medial-lateral ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-43 and Figure 4-44.

![Figure 4-43](image_url)

**Figure 4-43 – Medial-Lateral Ground Reaction force of all volunteers during the Asian squatting activity with weight shifting**
Figure 4-44 – Medial-Lateral Ground Reaction force of all volunteers during the Catcher’s squatting activity with weight shifting

The anterior and posterior ground reaction forces saw a similar trend for the Asian and Catcher’s squats with weight shifting. During the squats with weight shifting the ground reaction force became more anterior when weight was shifted onto the leg, and more posterior when weight was shifted off the leg. During the Asian squat the average maximum anterior ground reaction forces for all volunteers were 0.008 N/N on the right leg and 0.012 N/N on the left leg. During the Asian squat the average maximum posterior ground reaction forces for all volunteers were 0.005 N/N on the right leg and 0.005 N/N on the left leg. During the Catcher’s squat the average maximum anterior ground reaction forces for all volunteers were 0.016 N/N on the right leg and 0.019 N/N on the left leg. During the Catcher’s squat the average maximum posterior ground reaction forces for all volunteers were 0.014 N/N on the right leg and 0.009 N/N on the left leg. The anterior-posterior ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-45 and Figure 4-46.
4.4.3 Comparison of Ground Reaction Forces

The vertical ground reaction forces saw different trends for male and female volunteers. The Catcher’s squat saw similar trends between the males and females, with the beginning of the descent phase and the ending of the ascent phase of the squat causing
the vertical ground reaction force to decrease slightly. However, the Asian squat saw two different patterns for the male and female volunteers. The male volunteers showed a pattern similar to the Catcher’s squat, but the female volunteers showed only one peak in the vertical ground reaction force during the Asian squat. For male volunteers during the Asian squat the average maximum vertical ground reaction forces for were 0.593 N/N on the right leg and 0.539 N/N on the left leg. For female volunteers during the Asian squat the average maximum vertical ground reaction forces for were 0.559 N/N on the right leg and 0.553 N/N on the left leg. This is a decrease of 5.7% in the ground reaction force of the right leg when compared to the males, and an increase of 2.6% in the ground reaction force of the left leg when compared to the males. During the Catcher’s squat the average maximum vertical ground reaction forces for the male volunteers were 0.564 N/N on the right leg and 0.537 N/N on the left leg. During the Catcher’s squat the average maximum vertical ground reaction forces for the female volunteers were 0.555 N/N on the right leg and 0.545 N/N on the left leg. This is a decrease of 1.6% in the ground reaction force of the right leg when compared to the males, and an increase of 1.5% in the ground reaction force of the left leg when compared to the males. The vertical ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-47 through Figure 4-50.
Figure 4-47 – Vertical Ground Reaction Force of male volunteers during the Asian squatting activity

Figure 4-48 – Vertical Ground Reaction Force of female volunteers during the Asian squatting activity
The medial and lateral ground reaction forces saw a slightly different trend between the male and female volunteers. Before beginning of the squat and after the squat the ground reaction forces on the male and female volunteer were medial. As the volunteers descended the male volunteers’ ground reaction forces on the volunteer become more lateral. The female volunteers’ ground reaction forces became more lateral.
during the descent of the Asian squat, but stayed relatively the same during the Catcher’s squat. The male volunteers’ the ground reaction forces also switched from medial to lateral during both squatting activities, but the female volunteers’ ground reaction forces remained medial during the entire activity for both types of squats. During the Asian squat the average maximum medial ground reaction forces for male volunteers were 0.060 N/N on the right leg and 0.052 N/N on the left leg. The average maximum medial ground reaction forces for female volunteers were 0.060 N/N on the right leg and 0.052 N/N on the left leg. This implies that there were no differences between the maximum medial ground reaction forces between the male and female volunteers. During the Asian squat the average maximum lateral ground reaction forces for the male volunteers were 0.064 N/N on the right leg and 0.072 N/N on the left leg. The average minimum medial ground reaction forces for the female volunteers were 0.025 N/N on the right leg and 0.020 N/N on the left leg. This is a decrease of 139.1% in the lateral ground reaction force of the right leg when compared to the males, and a decrease of 127.8% in the ground reaction force of the left leg when compared to the males. During the Catcher’s squat the average maximum medial ground reaction forces for male volunteers were 0.066 N/N on the right leg and 0.058 N/N on the left leg. The average maximum medial ground reaction forces for female volunteers were 0.071 N/N on the right leg and 0.070 N/N on the left leg. This is an increase of 7.8% in the medial ground reaction force of the right leg when compared to the males, and an increase of 20.7% in the ground reaction force of the left leg when compared to the males. During the Catcher’s squat the average maximum lateral ground reaction forces for the male volunteers were 0.011 N/N on the right leg and 0.016 N/N on the left leg. The average minimum medial ground reaction
forces for the female volunteers were 0.056 N/N on the right leg and 0.048 N/N on the left leg. This is a decrease of 609.1% in the lateral ground reaction force of the right leg when compared to the males, and a decrease of 400.0% in the ground reaction force of the left leg when compared to the males. The medial-lateral ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-51 and Figure 4-54.

Figure 4-51 – Medial-Lateral Ground Reaction force of male volunteers during the Asian squatting activity
Figure 4-52 – Medial-Lateral Ground Reaction force of female volunteers during the Asian squatting activity

Figure 4-53 – Medial-Lateral Ground Reaction force of male volunteers during the Catcher’s squatting activity
Figure 4-54 – Medial-Lateral Ground Reaction force of female volunteers during the Catcher’s squatting activity

The anterior and posterior ground reaction forces saw a similar trend for the male and female volunteers. During the Asian squat the ground reaction force became more anterior during the beginning portion of the descent and ascent phases. During the Catcher’s squat the ground reaction force became more posterior during the descent phase and more anterior during the ascent phase. During the Asian squat the average maximum anterior ground reaction forces for the male volunteers were 0.012 N/N on the right leg and 0.011 N/N on the left leg. The average maximum anterior ground reaction forces for the female volunteers were 0.011 N/N on the right leg and 0.008 N/N on the left leg. This is a decrease of 8.3% of the anterior ground reaction forces in the right leg when compared to the males, and a decrease of 27.3% of the ground reaction force in the left leg when compared to the males. During the Asian squat the average maximum posterior ground reaction forces for the male volunteers were 0.006 N/N on the right leg and 0.007 N/N on the left leg. The average maximum posterior ground reaction forces for the female volunteers were 0.002 N/N on the right leg and 0.005 N/N on the left leg. This
is a decrease of 66.7% of the posterior ground reaction forces in the right leg when compared to the males, and a decrease of 28.6% of the ground reaction force in the left leg when compared to the males. During the Catcher’s squat the average maximum anterior ground reaction forces for the male volunteers were 0.014 N/N on the right leg and 0.018 N/N on the left leg. The average maximum anterior ground reaction forces for the female volunteers were 0.011 N/N on the right leg and 0.016 N/N on the left leg. This is a decrease of 21.4% of the anterior ground reaction forces in the right leg when compared to the males, and a decrease of 11.1% of the ground reaction force in the left leg when compared to the males. During the Catcher’s squat the average maximum posterior ground reaction forces for the male volunteers were 0.010 N/N on the right leg and 0.004 N/N on the left leg. The average maximum posterior ground reaction forces for the female volunteers were 0.010 N/N on the right leg and 0.006 N/N on the left leg. This is an increase of 50.0% of the posterior ground reaction forces in the left leg when compared to the males. The anterior-posterior ground reaction forces for the Asian and Catcher’s squats can be seen below in Figure 4-55 and Figure 4-58.
Figure 4-55 – Anterior-Posterior Ground Reaction force of male volunteers during the Asian squatting activity

Figure 4-56 – Anterior-Posterior Ground Reaction force of female volunteers during the Asian squatting activity
4.5 Summary

A summary of the maximum vertical ground reaction forces, maximum flexion angles, maximum joint moments, maximum muscle activities, and average muscle
activities for each of the four squatting activities can be found in Table 4-1 and Table 4-2 below. Paired t-tests with an alpha of 0.05 were used to determine the statistical significance of the results. Comparisons were done between the Asian squats and the Catcher’s squats and between weight shifting squats and non-weight shifting squats for the average of all volunteers. Additionally, comparisons were done between the male and female volunteers for each squatting condition. In the table below, cells highlighted in red show statistical significance between the Asian squat and Catcher’s squat. Cells highlighted in orange show statistical significance between the weight shifting and non-weight shifting condition, and cells highlighted in yellow show a statistical significance between male and female volunteers.
Table 4-1 – Summary of results found for Asian and Catcher’s Squats. GRF is normalized to N/N, joint moments are in Nm/kg, and muscle activities are normalized to a percentage of MVC.

<table>
<thead>
<tr>
<th></th>
<th>Asian Squat</th>
<th>Catcher’s Squat</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>All</td>
<td>Male</td>
</tr>
<tr>
<td>Max Right Vertical GRF</td>
<td>0.566</td>
<td>0.593</td>
</tr>
<tr>
<td>Max Left Vertical GRF</td>
<td>0.451</td>
<td>0.539</td>
</tr>
<tr>
<td>Right Knee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Flexion</td>
<td>123.6°</td>
<td>130.97°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.711</td>
<td>0.798</td>
</tr>
<tr>
<td>Left Knee</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Flexion</td>
<td>118.8°</td>
<td>122.54°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.609</td>
<td>0.595</td>
</tr>
<tr>
<td>Right Ankle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plantarflexion</td>
<td>15.66°</td>
<td>15.42°</td>
</tr>
<tr>
<td>Max Dorsiflexion</td>
<td>10.49°</td>
<td>10.34°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.239</td>
<td>0.204</td>
</tr>
<tr>
<td>Left Ankle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plantarflexion</td>
<td>16.31°</td>
<td>17.35°</td>
</tr>
<tr>
<td>Max Dorsiflexion</td>
<td>10.49°</td>
<td>8.72°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.279</td>
<td>0.258</td>
</tr>
<tr>
<td>Right Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Hamstring</td>
<td>14.4%</td>
<td>10.0%</td>
</tr>
<tr>
<td>Max Quadricep</td>
<td>104.9%</td>
<td>82.7%</td>
</tr>
<tr>
<td>Max TA</td>
<td>121.3%</td>
<td>85.2%</td>
</tr>
<tr>
<td>Max M Gastroc</td>
<td>63.8%</td>
<td>56.6%</td>
</tr>
<tr>
<td>Max L Gastroc</td>
<td>33.8%</td>
<td>39.0%</td>
</tr>
<tr>
<td>Left Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Hamstring</td>
<td>11.3%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Max Quadricep</td>
<td>116.0%</td>
<td>73.1%</td>
</tr>
<tr>
<td>Max TA</td>
<td>124.4%</td>
<td>151.7%</td>
</tr>
<tr>
<td>Max M Gastroc</td>
<td>54.4%</td>
<td>43.1%</td>
</tr>
<tr>
<td>Max L Gastroc</td>
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<td>45.3%</td>
</tr>
<tr>
<td>Right Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Hamstring</td>
<td>7.3%</td>
<td>4.7%</td>
</tr>
<tr>
<td>Average Quadricep</td>
<td>47.9%</td>
<td>36.5%</td>
</tr>
<tr>
<td>Average TA</td>
<td>55.6%</td>
<td>38.2%</td>
</tr>
<tr>
<td>Average M Gastroc</td>
<td>31.2%</td>
<td>21.8%</td>
</tr>
<tr>
<td>Average L Gastroc</td>
<td>18.9%</td>
<td>17.5%</td>
</tr>
<tr>
<td>Left Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Hamstring</td>
<td>6.2%</td>
<td>5.2%</td>
</tr>
<tr>
<td>Average Quadricep</td>
<td>50.2%</td>
<td>28.3%</td>
</tr>
<tr>
<td>Average TA</td>
<td>57.7%</td>
<td>67.9%</td>
</tr>
<tr>
<td>Average M Gastroc</td>
<td>26.0%</td>
<td>17.3%</td>
</tr>
<tr>
<td>Average L Gastroc</td>
<td>22.8%</td>
<td>17.0%</td>
</tr>
</tbody>
</table>
Table 4-2 – Summary of results found for Asian and Catcher’s Squats with weight shifting. GRF is normalized to N/N, joint moments are in Nm/kg, and muscle activities are normalized to a percentage of MVC.

<table>
<thead>
<tr>
<th></th>
<th>Asian Squat with Shifting</th>
<th>Catcher’s Squat with Shifting</th>
</tr>
</thead>
<tbody>
<tr>
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<td>All</td>
<td>Male</td>
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<tr>
<td>Max Right Vertical GRF</td>
<td>0.808</td>
<td>0.781</td>
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<tr>
<td>Max Left Vertical GRF</td>
<td>0.791</td>
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<tr>
<td>Right Knee</td>
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</tr>
<tr>
<td>Max Flexion</td>
<td>121.79°</td>
<td>130.46°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.951</td>
<td>1.013</td>
</tr>
<tr>
<td>Left Knee</td>
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<td></td>
</tr>
<tr>
<td>Max Flexion</td>
<td>115.96°</td>
<td>120.26°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.913</td>
<td>0.895</td>
</tr>
<tr>
<td>Right Ankle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plantarflexion</td>
<td>14.63°</td>
<td>14.70°</td>
</tr>
<tr>
<td>Max Dorsiflexion</td>
<td>16.35°</td>
<td>15.25°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.531</td>
<td>0.487</td>
</tr>
<tr>
<td>Left Ankle</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Plantarflexion</td>
<td>15.36°</td>
<td>16.09°</td>
</tr>
<tr>
<td>Max Dorsiflexion</td>
<td>17.39°</td>
<td>14.04°</td>
</tr>
<tr>
<td>Max Moment</td>
<td>0.594</td>
<td>0.556</td>
</tr>
<tr>
<td>Right Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Hamstring</td>
<td>14.5%</td>
<td>11.3%</td>
</tr>
<tr>
<td>Max Quadricep</td>
<td>134.2%</td>
<td>108.8%</td>
</tr>
<tr>
<td>Max TA</td>
<td>113.3%</td>
<td>75.2%</td>
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<tr>
<td>Max M Gastroc</td>
<td>68.3%</td>
<td>53.1%</td>
</tr>
<tr>
<td>Max L Gastroc</td>
<td>40.1%</td>
<td>34.0%</td>
</tr>
<tr>
<td>Left Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max Hamstring</td>
<td>15.0%</td>
<td>15.3%</td>
</tr>
<tr>
<td>Max Quadricep</td>
<td>141.0%</td>
<td>75.7%</td>
</tr>
<tr>
<td>Max TA</td>
<td>109.0%</td>
<td>129.6%</td>
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<tr>
<td>Max M Gastroc</td>
<td>122.1%</td>
<td>111.2%</td>
</tr>
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<td>Max L Gastroc</td>
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<td>80.4%</td>
</tr>
<tr>
<td>Right Leg</td>
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<tr>
<td>Average Hamstring</td>
<td>7.3%</td>
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<td>Average Quadricep</td>
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<tr>
<td>Average M Gastroc</td>
<td>29.1%</td>
<td>20.9%</td>
</tr>
<tr>
<td>Average L Gastroc</td>
<td>19.3%</td>
<td>14.4%</td>
</tr>
<tr>
<td>Left Leg</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average Hamstring</td>
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<td>5.2%</td>
</tr>
<tr>
<td>Average Quadricep</td>
<td>73.6%</td>
<td>37.5%</td>
</tr>
<tr>
<td>Average TA</td>
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<td>74.3%</td>
</tr>
<tr>
<td>Average M Gastroc</td>
<td>34.5%</td>
<td>21.6%</td>
</tr>
<tr>
<td>Average L Gastroc</td>
<td>23.4%</td>
<td>22.5%</td>
</tr>
</tbody>
</table>
Chapter 5

Discussion and Conclusion

5.1 Effect of A-C Squats on the Knee Joint

On average lifting the heels off the ground caused the knee extension moments to increase by 17.0% in the right leg and increased by 26.9% in the left leg. Knee extension moments continuously increased as the knee flexion angle increased. The maximum knee flexion angle experienced increased by 7.3% for the right leg and 8.5% for the left leg on average for all volunteers when lifting the heels off of the ground. However, only the knee flexion angle for the left knee was statistically different. The right leg also experienced a knee extension moment 16.7% greater than the left leg during the Asian squat and a knee extension moment 7.6% greater in the right leg during the Catcher's squat. Because the right leg saw greater knee extension moments, ankle plantarflexion moments, and ground reaction forces during all squats, it can be seen that these results were due to the volunteers primarily favoring their right leg for support during the
squatting motion, and not an effect of the squatting motion itself. The Catcher's squat significantly greater knee extension moments during the non-weight shifting cases. Weight shifting caused knee extension moments to significantly increase over the non-weight shifting cases, and weight shifting during the Catcher's squat caused the highest knee extension moments of all.

Therefore it can be seen that the Catcher’s position puts a greater strain on the knee joint during squatting. Because of this, the Catcher’s squat may cause more stress onto the cartilage in the knee joint. This stress could also be applied to implants in the knee, leading to greater wear over time.

**5.2 Effect of A-C Squats on the Ankle Joint**

On average lifting the heels off the ground caused the peak ankle plantarflexion moments to increase by 125.5% in the right leg and increased by 98.2% in the left leg. There were no significant differences in the maximum ankle plantarflexion or dorsiflexion angles experienced between the Asian and the Catcher’s squats. This implies that performing a Catcher's squat requires a greater ankle joint moment, but did not change the required range of motion for the ankle joint.

As with the knee joint, it was found that the ankle joint experiences greater moments during the Catcher’s squat, which can put more stress and damage onto the ankle joint.
5.3 Effect of A-C Squats on Muscle Activity

The activity of the quadriceps muscles generally increased as the knee flexion angle increased. The quadriceps muscles experienced a significant decrease of 20.2% of muscle activity in the right leg and a decrease of 14.8% in the left leg due to lifting the heels off of the ground. On average the quadriceps muscles experienced more activity during the Asian squat than during the Catcher's squat.

The tibialis anterior muscles activity also generally increased as the knee flexion angle increased. The tibialis anterior experienced a significant decrease of 59.8% in muscle activity in the right leg and a decrease of 54.5% in the left leg due to lifting the heels off of the ground.

Hamstring activity was relatively quiet throughout all squatting activities. There no significant differences between the Asian or the Catcher’s squats.

The medial and lateral heads of the gastrocnemius muscles also remained relatively unchanged throughout the squatting exercises. However, during the Catcher’s squat the muscle activities of the gastrocnemius increased when the heels were lifted off of the ground, and remained increased until the heels were placed back on the ground. The average muscle activities of the four muscles ranged from 18.9% to 31.2% during the Asian squat, and ranged from 28.3% to 56.9% during the Catcher's squat. This is an increase of 49.7% to the smallest average activity level, and an increase of 82.4% to the greatest average activity level. This was a significant difference between the two squatting positions.
It can be seen that the Asian squats require more muscle activity from the quadriceps and tibialis anterior muscles, while the Catcher’s squats require more muscle activity from both heads of the gastrocnemius muscle. Due to the body positions during the two squats, more muscle activity is required to maintain support during the Asian squat from the quadriceps and tibialis anterior muscles. This can lead to fatigue in the muscles faster, and make it more difficult for someone to squat in the Asian position if they are not used to it.

**5.4 Effect of A-C Squats on Ground Reaction Force**

The vertical ground reaction forces were very similar during the Asian and Catcher’s squats for all volunteers. Throughout both types of squatting activity the vertical ground reaction force was higher in the right leg, showing that the volunteers tended to favor their right leg for support during the squatting motion. There was a 6.2% increase in vertical reaction force in the right leg when compared to the left leg during the Asian squat and an increase of 3.5% in the ground reaction force of the right leg when compared to the left leg during the Catcher’s squat. During the beginning of the descent phase of the squat the vertical ground reaction force decreased slightly as the muscles acted to pull the legs up during in order to flex the joints. The same phenomenon happened during the ending of the ascent phase of the squat due to momentum helping to lift the person up.

The medial-lateral ground reaction forces were medial at the beginning of both types of squats. This was due to the volunteers standing with their feet spread between one and one-and-one-half shoulder-width apart, leading to a lateral force being placed on
the ground by the body weight. As the volunteers down the direction and magnitude of
the medial-lateral force corresponded greatly to the distance between the right and left
knee. Volunteers who squatted with their knees closer together tended to have a greater
medial ground reaction forces on them, while volunteers who squatted with their knees
further apart had greater lateral ground reaction forces. The Asian squat tended to
produce greater distance between the knees as most volunteers widened their knee
distance to be greater than their torso width in order to remain comfortable during the
descent of the squat. This lead to lateral ground reaction forces at the lowest point of the
Asian squat. During the Catcher’s squat the volunteers’ torsos did not get in the way of
comfort with the knees, so the distance that volunteers widened their knees varied during
the descent phase. This lead to the ground reaction forces becoming more neutral, but not
actually becoming a lateral force during the Catcher’s squat.

The anterior-posterior ground reaction forces had two distinct patterns for the
Asian and the Catcher’s squats. During the Asian squat the volunteers’ body weights
were centered behind the foot, so that the volunteer needed to produce an anterior
reaction force to help maintain balance. The ground reaction force was variable over the
squatting activity as balance needed to be adjusted, but was always an anterior force.
During the Catcher’s squat the center of mass for the volunteers was directly over the
foot, so that their weight was balanced and did not need much of an anterior or posterior
force for balance. This can be seen in the graphs when the anterior-posterior ground
reaction force hovers between 0.003 N/N anterior and 0.005 N/N posterior during the
portion of the squat where the volunteer has lowered themselves closer to the ground.
5.5 Effect of Shifting on the Knee Joint

On average shifting weight caused the knee extension moments to significantly increase by 33.8% in the right leg and increased by 49.9% in the left leg during the Asian squat. As body weight was shifting to one side of the body the knee extension moment increased on that side. As body weight was shifted away from one side of the body the knee extension moment decreased on that side. For the Catcher's squat weight shifting significantly increased the knee extension moment by 50.8% in the right leg and increased by 56.8% in the left leg. The maximum knee flexion angle did not significantly change during either the Asian or Catcher’s squats. This implies that shifting weight from side to side does not greatly change the flexion angle of the knee, but it increases the moment experienced by the knee. The Catcher's squat caused a greater increase in the knee extension moment when weight shifting occurred. This could be due to volunteers being able to shift their weight more easily during the Catcher's squat than during the Asian squat or due to the difference in moment arm between the two positions.

Because of this, it can be seen that weight shifting causes knee extension moments to increase over the non-weight shifting cases. This puts more stress on the joint, leading to a greater change of wear over time the more that weight shifting occurs. Furthermore, squatting in the Catcher’s position causes the greatest amount of knee extension moment when weight shifting when compared to the other three conditions.
5.6 Effect of Shifting on the Ankle Joint

On average shifting weight caused the ankle plantarflexion moments to significantly increase by 122.2% in the right leg and increased by 112.9% in the left leg during the Asian squat. As body weight was shifting to one side of the body the ankle plantarflexion moment increased on that side. As body weight was shifted away from one side of the body the ankle plantarflexion moment decreased on that side. For the Catcher's squat weight shifting significantly increased the ankle plantarflexion moment by 28.2% in the right leg and increased by 34.2% in the left leg. The maximum ankle dorsiflexion angle experienced during the Asian squat significantly increased by 53.5% for the right leg and 65.8% for the left leg on average for all volunteers when shifting weight from side to side. The maximum ankle dorsiflexion angle experienced during the Catcher’s squat significantly increased by 31.4% for the right leg and 33.4% for the left leg on average for all volunteers when shifting weight from side to side. The maximum ankle plantarflexion angle experienced did not significantly change during either the Asian or Catcher’s squats when shifting weight from side to side.

It can be seen that shifting weight from side to side increases the dorsiflexion angle and the plantarflexion moment experienced by the ankle. When weight is shifted onto one leg, it causes the ankle to begin to buckle under the added support, and causes a greater dorsiflexion. The greater dorsiflexion angle and plantarflexion moment can cause greater stress on the joint, which may lead to greater wear if weight shifting occurs often or for longer periods of time.
5.7 Effect of Shifting on Muscle Activity

There were very few significant differences in the muscle activities between the weight shifting and non-weight shifting cases. During weight shifting muscle activities tended to increase, except for the tibialis anterior during the Asian squat and the gastrocnemius during the Catcher’s squat, which tended to decrease in activity due to weight shifting. There were some muscle activities that were significant to an alpha level of 0.1, but there were only 2 muscle activities in each of the Asian and Catcher’s squats that showed significance to the 0.05 level. Expanding the number of volunteers in the future may help to show more significance between the muscle activities of weight shifting and non-weight shifting conditions.

5.8 Effect of Shifting on Ground Reaction Forces

Weight shifting had a large effect on the vertical ground reaction forces during both the Asian and Catcher’s squats. During both squats shifting weight onto one leg caused an increase in the vertical ground reaction force of that leg while causing a proportional decrease in the ground reaction force of the contralateral leg. For both the Asian and Catcher’s squat the volunteers were able to shift more of their weight onto their right legs.

The medial-lateral and anterior-posterior ground reaction forces were less distinct when shifting body weight, but they followed a similar trend as the vertical reaction forces. When weight was shifted onto one leg the lateral and anterior forces on that leg increased, while they decreased on the contralateral leg.
5.9 Male and Female Comparison of Knee Moment

The male and female volunteers both followed the same trends as the averages for all volunteers together. While the male volunteers tended to have greater knee extension moments and knee flexion angles than the female volunteers, there were no significant differences between the male and female volunteers in the values. This suggests that the squatting postures have the same effects the knee joint regardless of gender, but increasing the sample population would help to improve this conclusion. This is also the case in the other comparisons made between the male and female volunteers.

5.10 Male and Female Comparison of Ankle Moment

The male volunteers tended to have greater ankle plantarflexion angles, while the female volunteers tended to have greater ankle dorsiflexion angles and plantarflexion moments than the male volunteers. However, as with the knee joint, the ankle joint had no significant differences between the male and female volunteers for any of the four conditions.

5.11 Male and Female Comparison of Muscle Activity

Male and female volunteers both showed the same trend in muscle activity during the squatting exercises. There were only a few statistical differences between the muscle activities of the male and female volunteers, but there was no consistency between the differences to indicate a distinct difference in the muscle activities due to gender. In general, the male volunteers tended to have less muscle activity, even though it was not significantly different.
5.12 Male and Female Comparison of Ground Reaction Forces

The vertical ground reaction forces were mostly similar between the male and female volunteers with a few small differences. One difference was that the male volunteers tended to put a greater proportion of their weight onto their right legs while the females tended to be more evenly distributed during both the Asian and Catcher’s squats. The other difference was that the male volunteers had two peaks in the vertical ground reaction forces while the females only had one peak in the vertical ground reaction force. This is most likely due to the speed at which the Asian squats were performed between the two groups. The male volunteers tended to take a little longer to complete the Asian squat activity, causing a slight pause between the peak force from stopping the descent and starting the ascent, whereas the female volunteers tended to take less time between the end of the descent and the beginning of the ascent.

The medial-lateral ground reaction forces were also different between the male and female volunteers. Both the male and female volunteers started with medial ground reaction forces for the Asian and Catcher’s squats. During both squatting activities that male volunteers reached a lateral ground reaction force at the lowest point of the squat, but the female volunteers had medial ground reaction forces throughout all squatting activities. This was because the female volunteers tended to keep their knees closer together during the squatting activities. Furthermore, the female volunteers had very little variation in their medial forces during the Catcher’s squat. This was due to the female volunteers keeping their knees at about the same distance apart throughout the Catcher’s
squatting activity, where the males tended to widen the distance between the knees quite a bit during the activity.

The anterior-posterior ground reaction forces followed the same trends for the male and female volunteers during the Catcher’s squat, with very little difference between them. The ground reaction forces also showed a similar trend during the Asian squat, but differences in the required balance adjustments for the male and female volunteers caused the ground reaction force to change at different times.

5.13 Conclusion

Through this study it was found that the Catcher's squat caused greater knee extension moments and greater plantarflexion moments than the Asian squat. Additionally, the Catcher's squat caused the muscle activity in the quadriceps and tibialis anterior muscles to decrease, and the muscle activity in the gastrocnemius muscles to increase. Weight shifting caused knee extension moments and ankle plantarflexion moments to increase over the non-weight shifting cases for both the Asian and the Catcher's squats as weight was placed onto one leg. The weight shifting also caused an increase in the ankle dorsiflexion angle as more weight was placed onto one leg and caused the ankle to shift to support more weight. The muscle activities tended to increase during weight shifting, but did not change significantly. Due to the increase in joint moments and angles, more stress may be placed on the joints when squatting in the Catcher’s position for extended periods of time, and can cause greater wear to the knee and ankle joints. However, the increased muscle activity makes it harder to maintain the Asian squat for long periods without first getting used to it. Weight shifting should also
be avoided if possible so that extra stress is not put on the knee and ankle joints. Therefore, it is recommended that the Asian squat be considered when squatting for extended periods of time, however, it must be practiced and built up to so that weight shifting does not occur to maintain comfort in an unfamiliar squatting position. Weight shifting should also be avoided if possible, and should instead be replaced with standing in order to relax the muscles and relieve the joints of the increased moments.
References


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